

Robotics Research Technical Report

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A Crank Turning Algorithm for the
Four Finger Manipulator

by

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Technical Report No. 330
Robotics Report No. 127
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Abstract

A force/position control algorithm has been developed for the Four Finger Manipulator to turn a crank. The axis of rotation of the crank is unknown. The algorithm accounts for a varying load distribution on the crank.

A Crank Turning Algorithm for the Four Finger Manipulator

Gerardo Lafferriere
Deepak Mohan

November 20, 1987

1 Introduction

We describe here a control algorithm for the Four Finger Manipulator to turn a crank. The NYU Four Finger Manipulator (FFM) is a two dimensional robot designed and fabricated at the NYU Robotics Laboratory to study dextrous manipulation and problems associated with real time control of robots. A schematic representation of the system (top view) is shown in Figure 1.1.

Most robots in use today are primarily position controlled and hence need very accurate programming. Moreover they are not well suited for dealing with an uncertain or partially known environment. The FFM group at NYU has been involved in developing more versatile control algorithms for robots, using force/position feedback information, specially in problems involving coordination of several fingers. One such problem is that of using several fingers to grip and manipulate an object which is constrained by various hinges, pegs and slots to move along an unknown path while keepings the constraint generated forces to a minimum. We studied this problem both with and without external forces acting on the system. Examples of such systems would be :

1. Turning a crank,
2. Opening a door (Spring loaded/No Spring),
3. Turning a wrench.

In [4] we developed and implemented two algorithms for the following tasks:

Task 1: "Hold a knob and open a simple door". In this case there are no external forces acting on the door, and initially an approximate starting direction has to be specified.

Task 2: "Push open a spring loaded door". In this case an external force acts on the door.

However these algorithms were not general enough to perform the more complicated task of turning a crank in the presence of a varying external load. The first algorithm was designed for the case when there are no external forces acting on the door. In the second case, when an external force is present the robot could only push the door. It was unable to grasp the knob while opening it. We have now developed a single more general algorithm that can turn a crank as well as open a door, when the axis of rotation is unknown and a varying load distribution might be acting on the system.

2 Problem Specification

The problem is to develop an algorithm that would enable the FFM to turn a crank. The axis of rotation of the crank is unknown. An external load (which may be varying with time) could be acting on the system. This is typical in many cases when the robot needs to perform a cranking motion to do some work. Examples would be :

- (i) turning a car jack,
- (ii) rolling up a shutter,
- (iii) rolling up/down car windows,
- (iv) lifting up a barrel of water with a pulley arrangement,
- (v) bicycling.

3 The Algorithm

The problem consists of two steps:

- (a) grasp the crank handle (knob),
- (b) Move the center of the handle along the arc of a circle, maintaining the grip and accepting all external forces that might be acting on the system.

The *virtual finger* approach [4,1] enables the experimenter to consider a grasped body and the fingers as a single unit. In our case we can reduce the fingers and the crank handle to one reference point (center of handle) and can henceforth use this fact to develop our algorithm.

We now define some terminology that will be used throughout this report. By *internal* forces we mean forces at the reference point generated by the gripping fingers or by the internal mechanical constraints of the system. *External* forces are the friction forces or load acting on the system. In our case external forces are generated by hanging weights from the crank. *Tangential* forces are forces tangent to the trajectory of the reference point. *Normal* forces are forces along the length of the crank arm at the reference point. These are perpendicular to the tangential forces.

Decomposition of forces in this manner enables us to effectively obtain a solution to this problem. Due to the discrete nature of the system and the

approximate algorithms some internal forces are generated in the system. In addition there are external forces present. The axis and the radius of the crank are unknown. The goal of the algorithm is to accept the external forces and set the internal forces to zero while maintaining the prescribed gripping forces.

The following remarks are immediate consequences of the mechanics of the system.

Remark 3.1 Any normal component of the external force on the crank will be absorbed by the crank pivot. The FFM will have to overcome only the tangential component of the force on the reference point P of the handle (see Figure 2).

Remark 3.2 The internal forces are generated due to the discrete and approximate nature of the motion. Figure 3 shows the computed motion $\widehat{PQ}$ and the actual motion $\widehat{PP_+}$ after one control cycle of a typical experiment. Errors create a normal force along OP which is absorbed by the finger compliances.

This shows that in our system the internal forces are the normal forces and the external forces are the tangential forces. Thus, at any stage, given the force readings, we need to estimate the tangent to the direction of motion. At every cycle we can then accept the tangential forces and set the normal forces to zero. (This is essentially the hybrid force/position control approach [5].)

At any point on the trajectory of motion the situation can be viewed as in Figure 2. The co-ordinates of the point O and the radius r are unknown. There is a force F acting in some direction. In order to determine the tangential direction to the circle described by OP additional information is needed (See Figure 4). We use a past history of reference point positions. (Notice that these are obtained using the past finger (top) positions together with their forces and the precalibrated finger compliances.) If only two points are used, say the current position P and the previous position P_- , then $\widehat{P_-P}$ gives an approximation of the tangent vector. If more points are used a suitable curve could be fit to the points and the tangent to such a curve could be used as the desired approximation. A two point estimate was quite suitable for our experiments. To compute the target position for the next control cycle we extend the vector $\widehat{P_-P}$ by δx to the point N . The algorithm can be summarized briefly as follows:

```

if cycle_number <> 1 then
  get current_position readings;
  get current_force readings;
  compute tangent direction = current_position - old_position;
  decompose forces in normal and tangential direction;
  compute target forces such that normal comp. = 0 and tan. comp. = tan. comp. of actu
  target_position = current_position + dx in tangent direction;
  old_position = current_position;
else
  old_position = current_position;
  target_position = (specify initial direction);

```

We see that an approximate direction of initial motion has to be given. This is justified as the robot manager should specify as to which direction should the crank be turned.

The target forces are calculated as follows:

$$F_{\text{actual}} = (F_{\text{actual}} \cdot t)t + (F_{\text{actual}} \cdot n)n$$

F_{actual} : actual force vector
 t : tangent direction vector
 n : normal direction vector
 $F_{\text{target}} = (F_{\text{actual}} \cdot t)t$

This determines the target forces and positions for the gripped object. The finger force and position targets are then obtained using a (linear) transformation computed at the time the grip was established (see [1]). Finally, a linear spring model for the fingertips is used to combine these targets into the position commands to be issued to the stepper motor (via the inverse kinematics).

4 The Experimental Setup

The FFM consists of four identical and independently controllable fingers (see Figure 1.2) that are mounted on the four sides of a square table. Each finger can be moved in the xy -plane with the aid of two stepper motors that are connected to the finger through a system of carriages and links. In all the robot has eight degrees of freedom (2×4 fingers). Each finger is compliant, and has two pairs of strain gauges that enable it to sense the x and y component of the force acting on the finger. The accuracy of the strain gauges is about 0.01 N. Each of the eight stepper motors is

controlled by an INTEL 8088 processor and has a position encoder attached to it. These processors, along with the other precision components provide a position accuracy of about 0.001 cm. Together, the strain gauges and motor encoders provide all the information required for force/position control of the system. The mounting table can be tilted to perform experiments in the presence of gravity.

The setup for these experiments is shown in Figures 5–7.2. The crank consists of a spool and a knob. The spool (Fig. 5) is 2.25 in. in diameter and 0.25 in. thick. It has a center hole and two other holes at 0.75 in. and 0.62 in. from the center. These holes are used to mount the knob. The spool is mounted on the FFM table through a center hole and can rotate freely. A thread is attached in the groove and goes over a pulley at the edge of the table. Weights can be hung down this thread (Fig. 7.2). The weights provide the external force.

The knob (Fig. 6) is 2.25 in. in diameter and 0.5 in. thick. It has a hole in the center to attach it to the crank. The knob can rotate freely about this point. The sizing of the fixtures was done to accommodate the robot workspace constraints.

Fig. 7.1 shows a schematic diagram of the spool and the knob in position. The spool and the knob both can rotate about their centers. The knob is placed at an offset (0.75 or 0.62 in.) from the center of the spool. A thread is attached to the spool and weights can be attached to the end of the string, and hung down the table. External forces can be varied by removing and adding weights at the end of the string. Maximum weight limits are determined by the finger safety limits. As the robot turns the spool by grasping the knob, the weight is lifted and the thread winds around the groove in the spool. Fig. 7.2 gives a schematic view of the complete system.

5 Test Results

Several tests were carried out to check this algorithm. These include

- (a) No external force on the crank,
- (b) 50 g external weight,
- (c) Different crank arm length.
- (d) Varying load on crank.

The crank was placed at an arbitrary position on the table. Then tests were carried out to check the accuracy and robustness of the algorithm. The crank arm length used for case (a) and (b) was 0.75in. and for case (c) was 0.62 in. The total number of control cycles in each case was 1000 and the step size used was 0.03 cm. This step size was found to be ideal after several tests. A smaller size slows down the experiment, although the internal force build up was less, and a larger size makes the motion erratic.

5.1 Test (a). No external force on the crank.

In the first test, the crank was placed on the table, with no external forces acting on it, i.e. no weights hanging down the thread. In principle this case reduces to the "door opening" case in [4]. The experimental results for this case are shown in Fig. 9–12. The forces on the reference point should be small as there are no external forces. The forces seen in Fig. 9 are the internal forces generated during the motion. The magnitude remains small (0.25 N) as can be seen from Fig. 9.2. Fig. 11 shows the forces on individual fingers. The forces seen here include the gripping forces, hence the range is between 1 to 1.5 N. Fig. 10 shows the actual path of the reference point and the estimated directions. As one would expect, the trajectory of the reference point is a circle. The approximation used to obtain the tangent direction (see Fig. 4) is seen to work fairly well for a small step size of 0.03 cm. One should compare this approach for obtaining tangent directions to that in [4], where only force readings were used to compute directions. Fig. 12 shows the torque on the reference point. As expected the value should be close to zero, as the knob is free to rotate about its center.

5.2 Test (b). 50 g external weight.

In the second experiment a weight of 50 g was hung down the pulley. Fig. 13 shows the forces on the reference point. Initially the force on the reference point is zero, as the force is being accepted by the base of the crank. Once the crank starts turning, the string gets taut and the force builds up on the knob. The algorithm differentiates between internal and external forces. The robot accepts a changing external force as can be seen from Fig. 13.2. In Fig. 13.2 at about 400 cycles a small hump is seen. Such behavior is possible as the algorithm is approximate and self adjusting/correcting. Soon afterwards this force buildup is corrected. As long as the safety limits are not exceeded, these corrections can take place. Fig. 14 shows the actual path and the estimated directions. Data loss in the communication (ethernet)

between the fileserver and the low level controller produced the stray arrows in Fig. 14.2. Fig. 15 shows the sinusoidal behavior of the forces on each finger. As the crank is turned, individual fingers are continuously changing their position with respect to the load. Depending on the finger position and the direction of motion, different fingers will be accepting the external forces at different times (Fig. 8.1). The external force is acting tangent to the circle at every point. At position P_1 fingers 1 and 2 are accepting the external forces. At position P_2 fingers 1 and 3 are accepting the forces, and similarly at P_3 finger 3 is accepting most of the external force. Hence the force distribution on individual fingers changes continuously. This is the behavior depicted in Fig. 15. Fig. 16 shows the torque which, as explained earlier, is close to zero.

5.3 Test (c). Smaller crank arm length.

The crank has provision to have a different arm length. The same algorithm was run with the smaller arm length (0.62 in.) and a weight of 50 g was hung. This experiment demonstrates that the algorithm is not a function of the crank arm length. In fact, the algorithm is independent of the shape of the trajectory of the reference point (a circle in our case) as long as it is smooth (no corners). Figs. 17–20 show the behavior of the system. As the crank arm length is smaller, we find that, compared to case (a), the magnitude of forces built up is higher. This is due to the fact that with the same step size and a smaller arm length, the internal force build up at every cycle will be more. Fig. 8.2 shows this feature graphically. There is a greater error dx at every cycle when a smaller crank arm length is used, for the same step size. Fig. 18 shows the actual path and the estimated directions. Fig. 19 shows the forces on each finger. We see here a higher frequency than in case (a) as expected (given the same number of cycles and the same stepsize a smaller crank arm length would give more rotations). Fig. 20 shows the torque on the reference point.

5.4 Varying load on crank

Experiments were conducted varying the load on the crank arbitrarily from 0 to 50 g. A weight of 50 g was hung down the thread and while the crank was in motion, it was arbitrarily lifted and dropped by hand to generate an unknown varying force.

The algorithm performed very well, and the results can be seen in Figs. 21–24. Fig. 21 shows the force on the reference point. The force can be seen

to vary arbitrarily from Fig. 21.2. Fig. 22.2 shows the estimated direction which at every point is tangent to the circle. The algorithm shows low sensitivity to external load variations. Figs. 23 and 24 show the finger forces and reference point torque respectively. Force buildups stay well within the safety limits (about 3 N).

6 Conclusions and remarks

We have successfully implemented a force/position control algorithm that enables the NYU Four Finger Manipulator to turn a crank. A varying external force could be acting on the system. This algorithm is more general than the one in [4].

The algorithm was found to be very robust with respect to changes in system parameters and external loads. Experiments were run with different crank arm length, external load and an arbitrarily varying external load. The system behaved well. Accurate estimates of tangent directions were obtained constantly, and the force build up on the fingers was well within safety limits (about 3 N).

Our approach can be extended to other multifinger manipulators. One such extension is planned for our Utah/MIT dextrous hand.

7 Acknowledgements

We want to thank everyone in the FFM project at NYU for their support and cooperation. In particular we would like to thank Mr. Fred Hansen for designing and fabricating the crank fixtures used in this experiment.

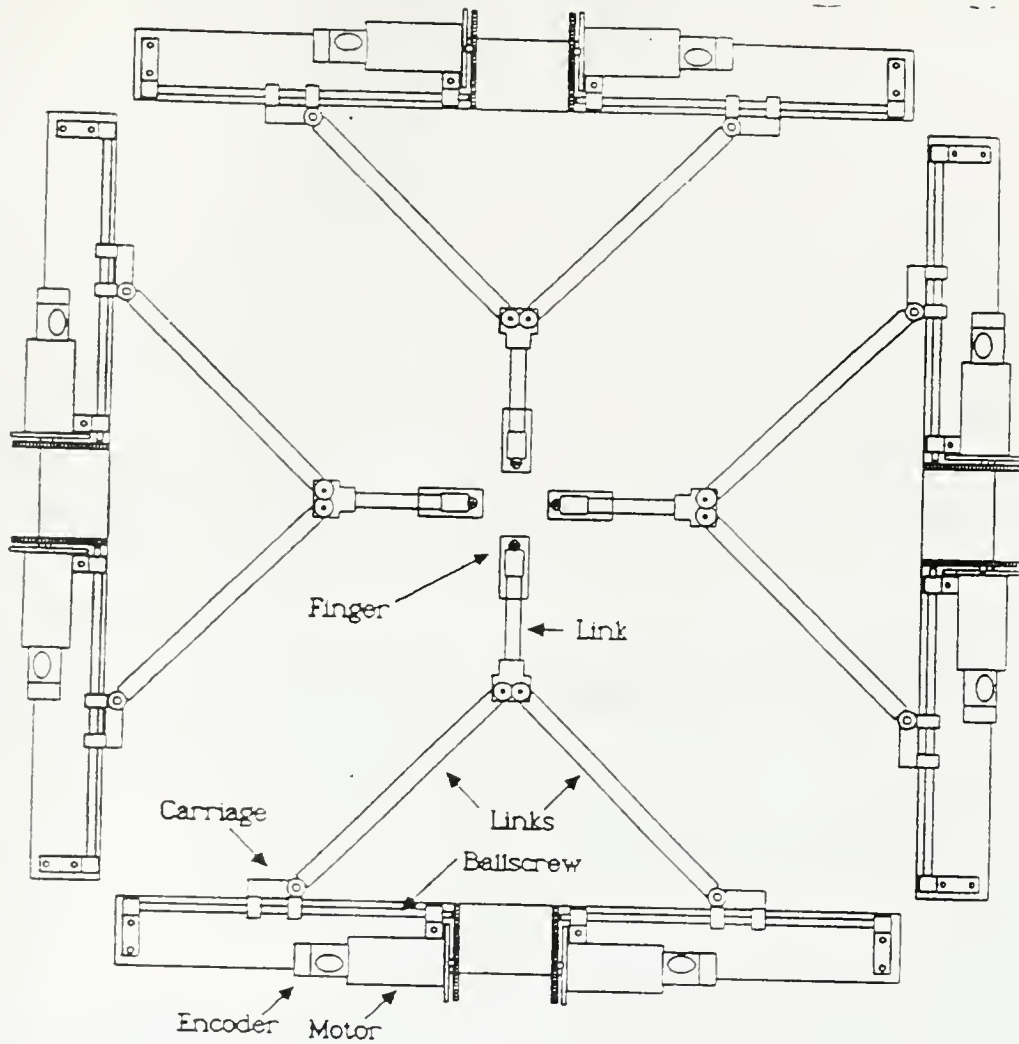


Figure 1.1: Layout of the Four Finger Manipulator (top view)

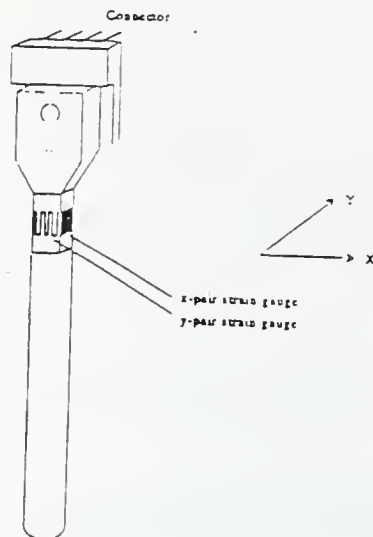


Figure 1.2: Finger tip (side view)

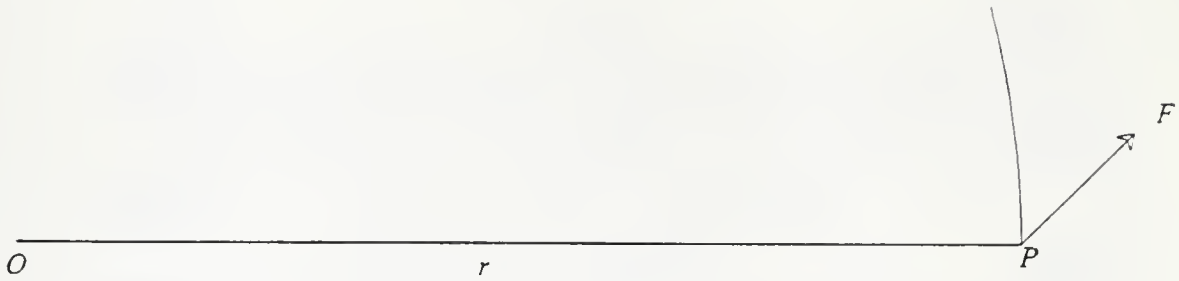


Figure 2: Force at any instant

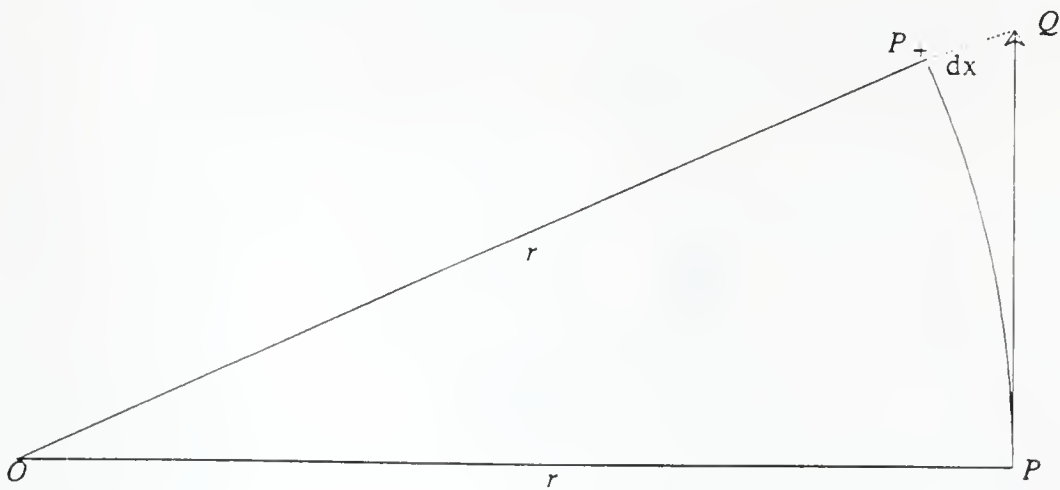
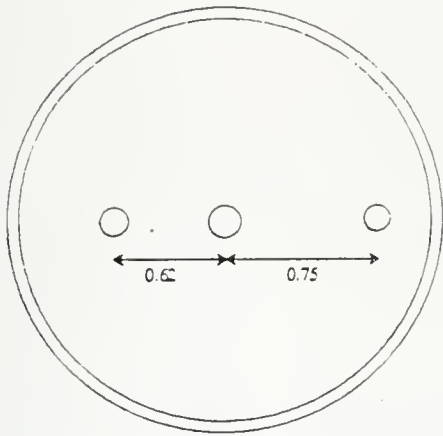


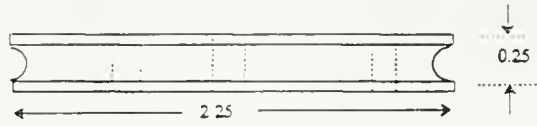
Figure 3: Generation of Internal forces



Figure 4: Estimation of tangent



TOP VIEW

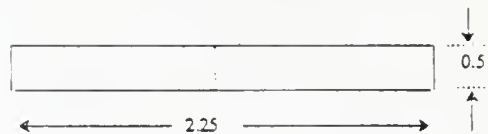


SIDE VIEW

Figure 5: The Crank Spool



TOP VIEW



SIDE VIEW

Figure 6: The Crank Knob

NOTE: Drawings are not to scale

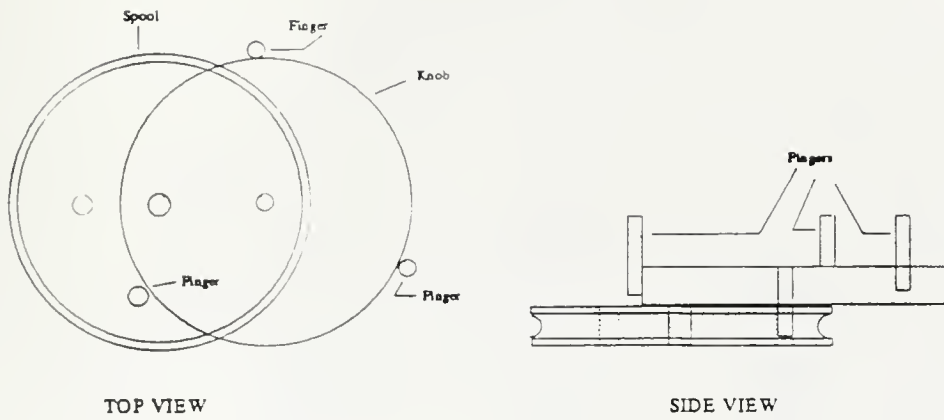


Figure 7.1: The Crank in position

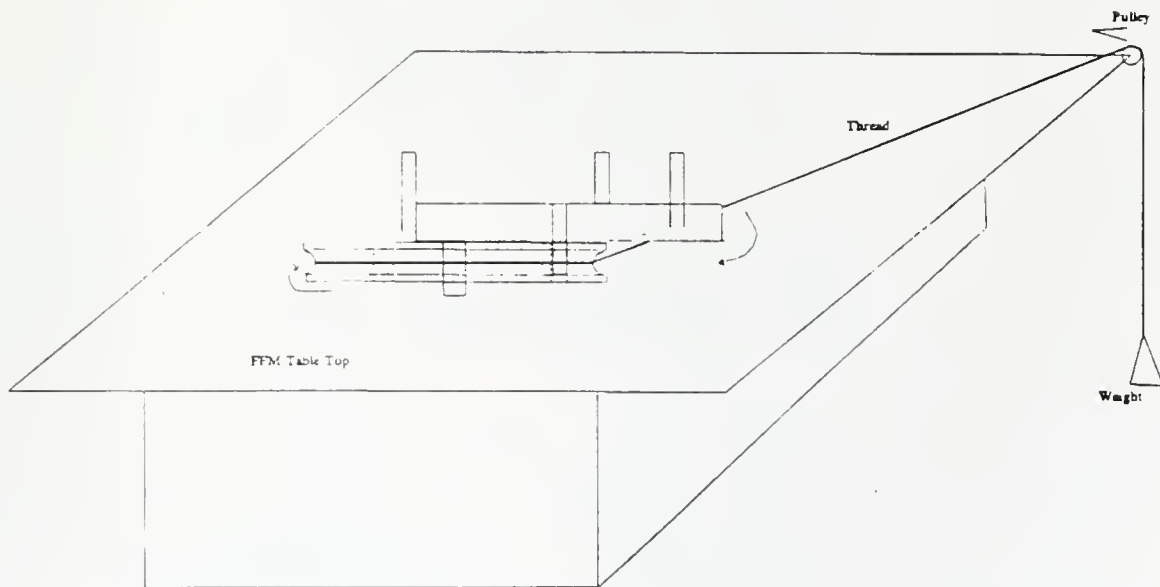


Figure 7.2: Schematic diagram of the system layout

Note: Drawings are not to scale

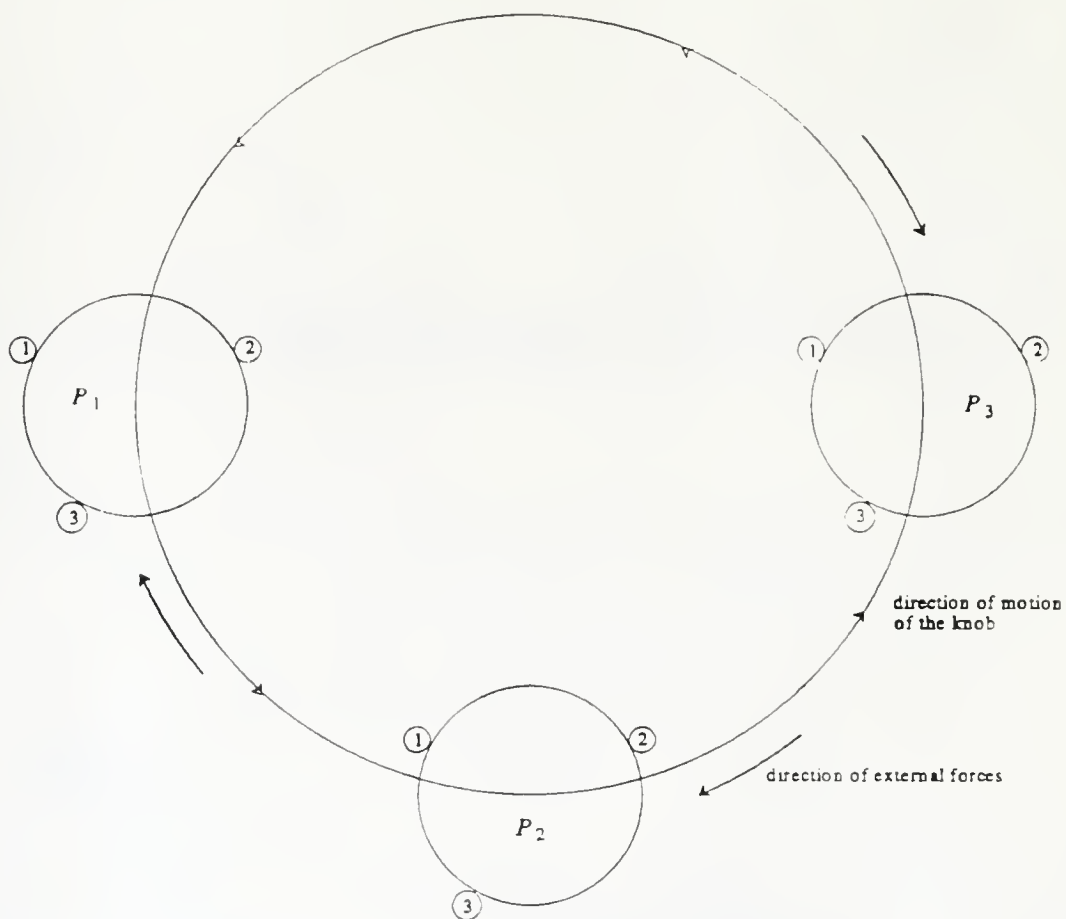


Figure 8.1: External forces on fingers

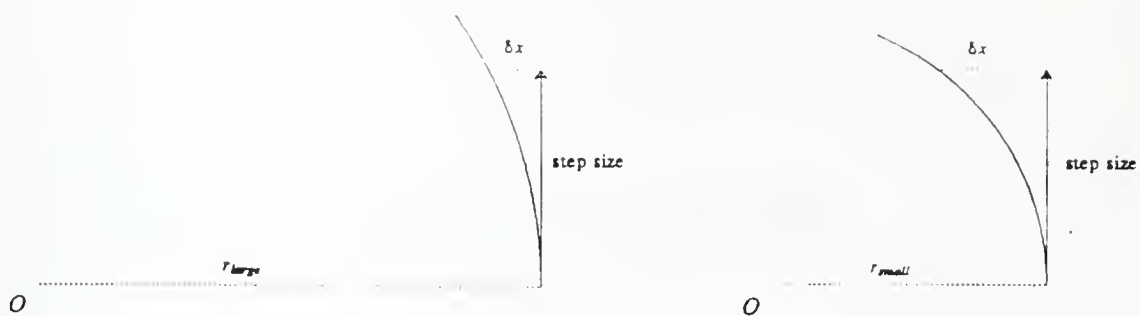


Figure 8.2: Internal force generation

Figure 9: Forces on reference point
(No load on crank)

Figure 9.1: Actual forces

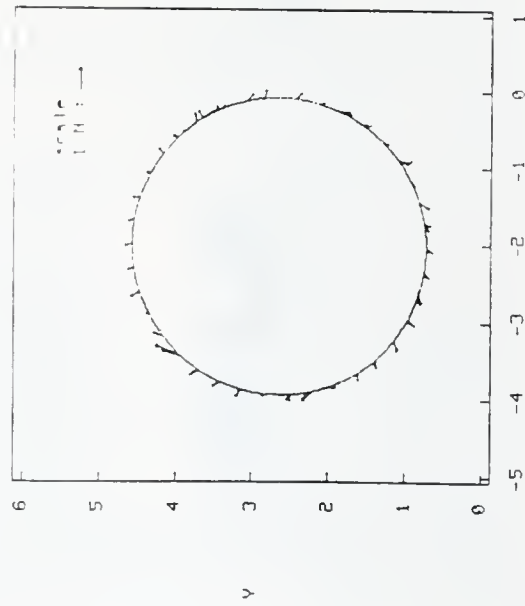
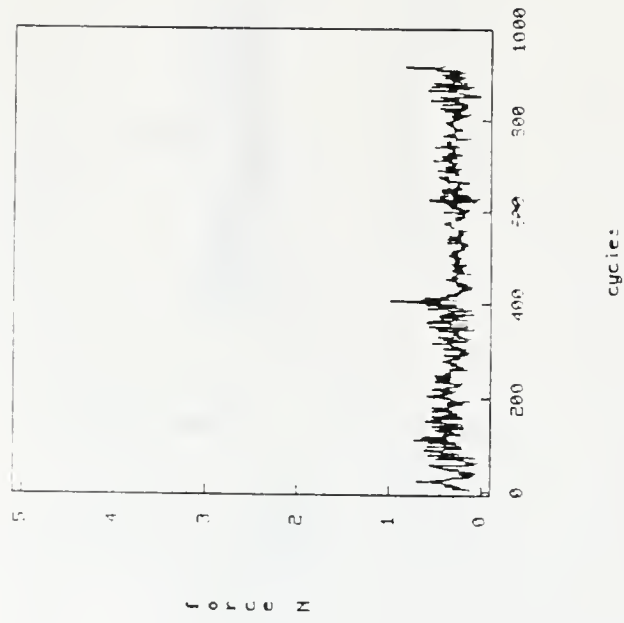


Figure 9.2: Magnitude of forces



ref. point location X. (cm)

cycles

Figure 10: Estimated and Actual paths
(No load on crank)

Figure 10.1: Actual path of ref. point Figure 10.2 Estimated directions

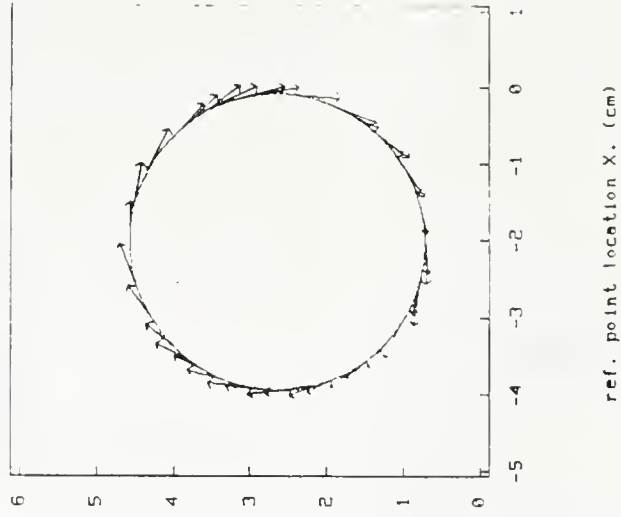
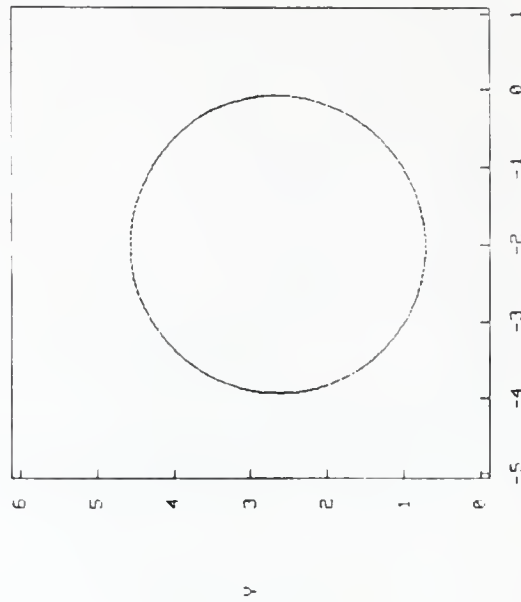


Figure 11: Forces on each finger
(No load on crank)

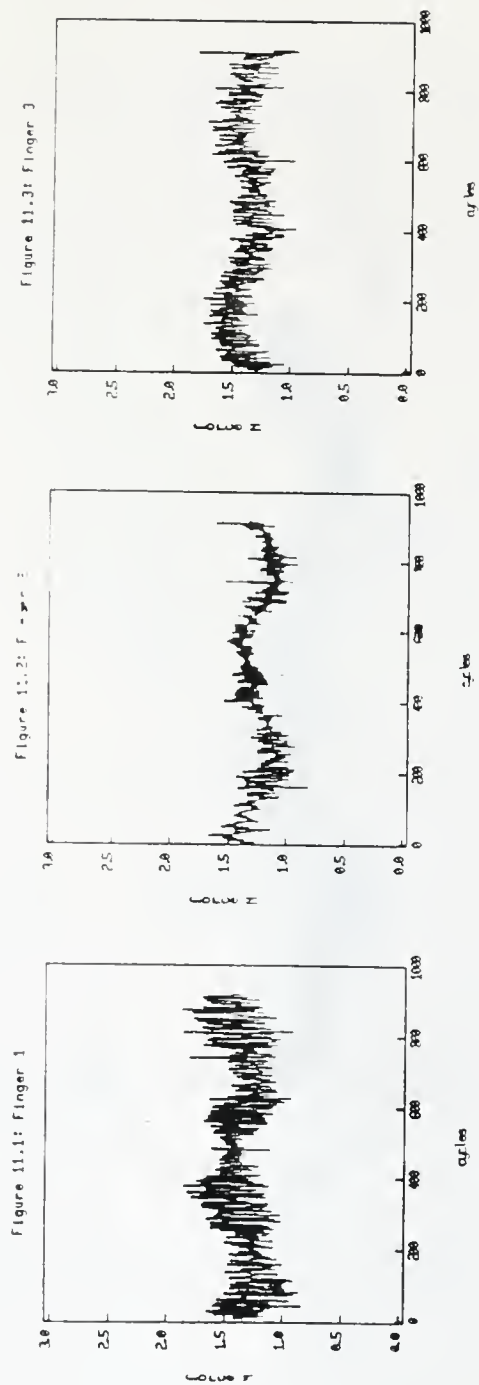


Figure 12: Torque on the reference point
(No load on crank)

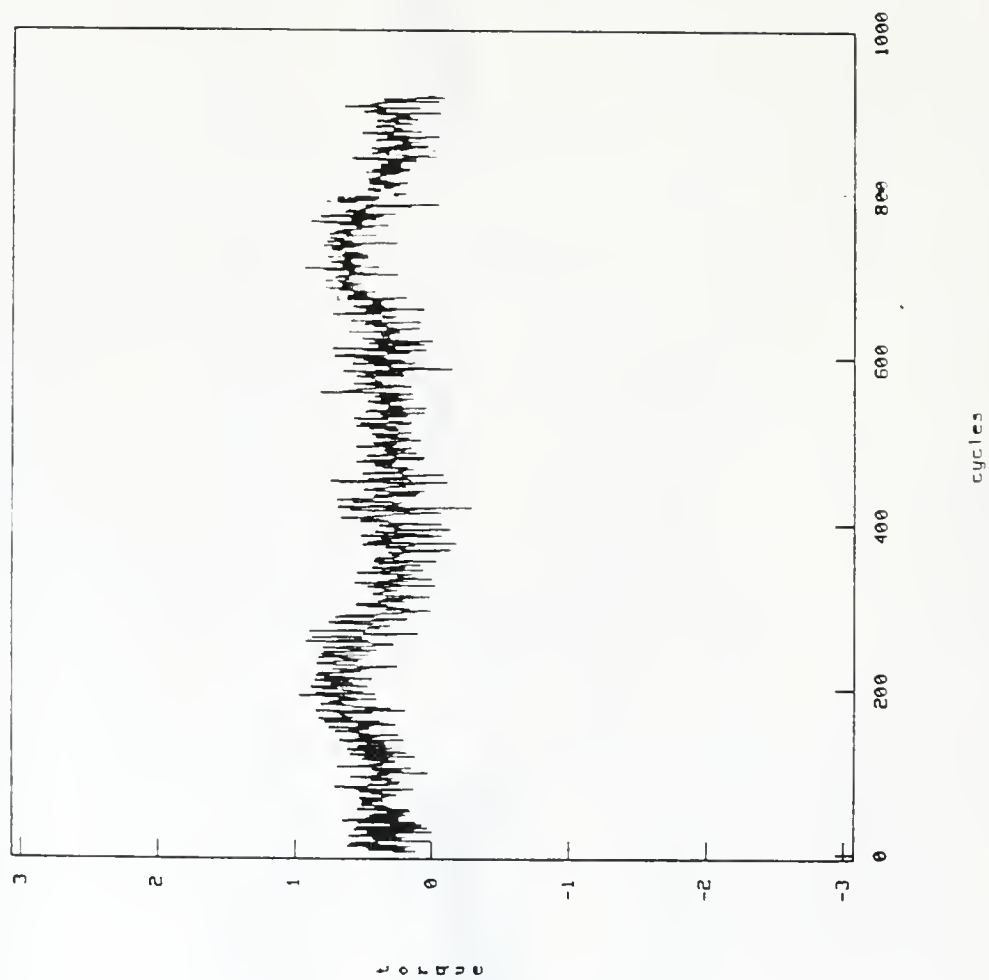


Figure 13: Forces on reference point
(50 g hanging weight)

Figure 13.1: Actual forces

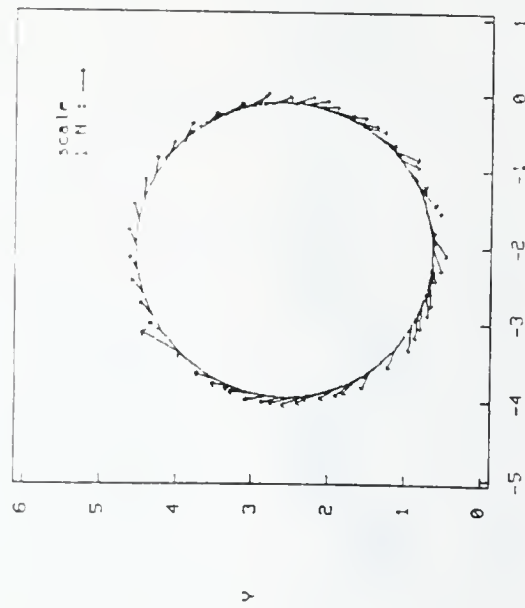


Figure 13.2: Magnitude of forces

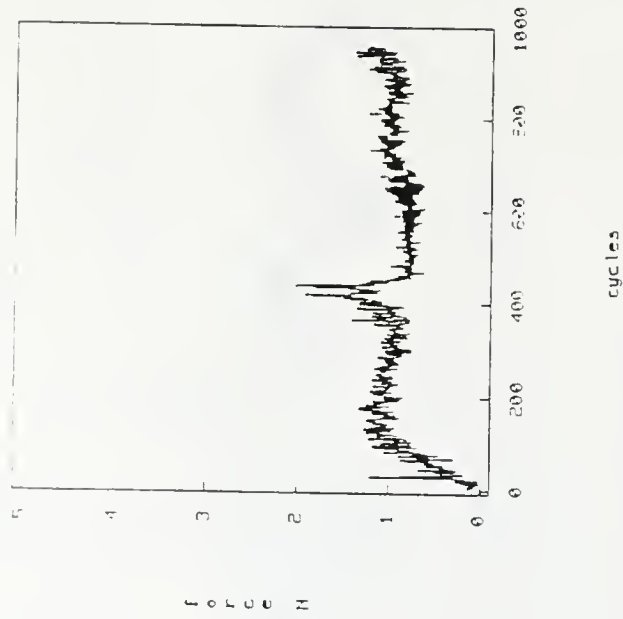


Figure 14: Estimated and Actual paths
(50 g hanging weight)

Figure 14.1: Actual path of ref. point

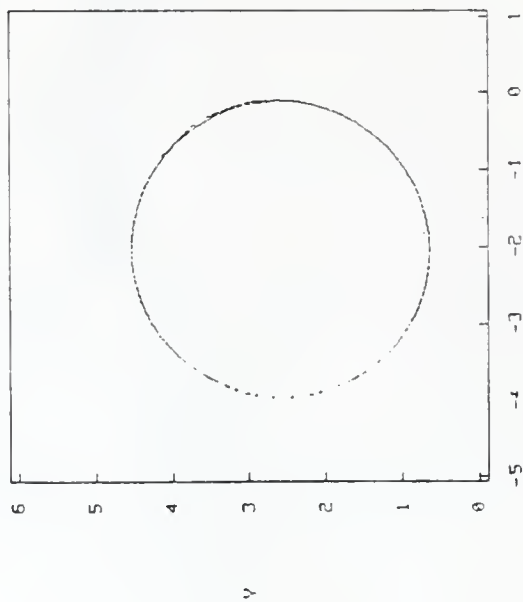


Figure 14.2: Estimated directions

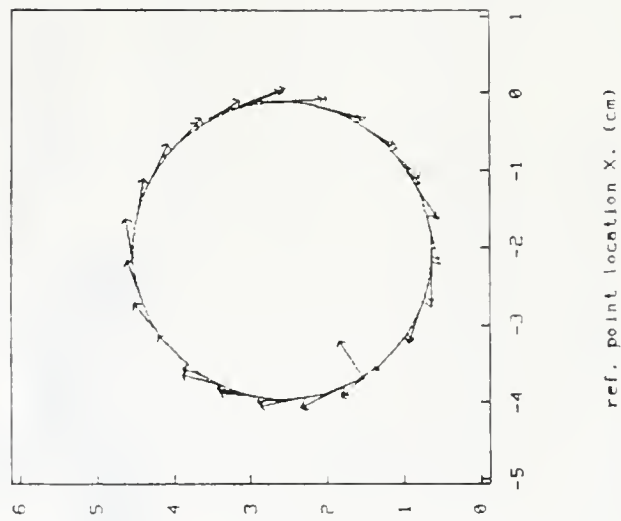


Figure 15: Forces on each finger
(50 g hanging weight)

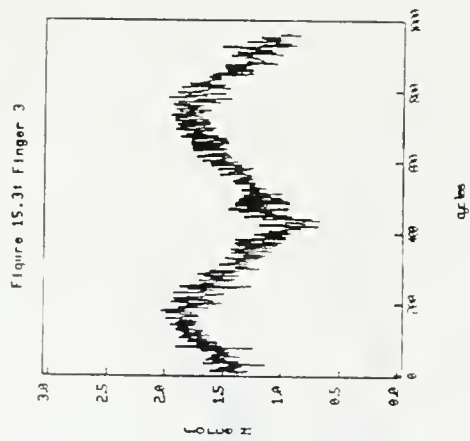
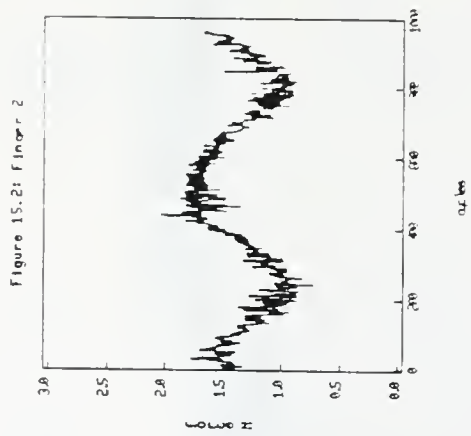
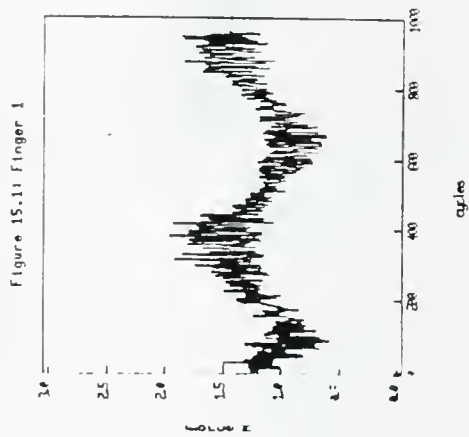


Figure 16: Torque on the reference point
(50 g hanging weight)

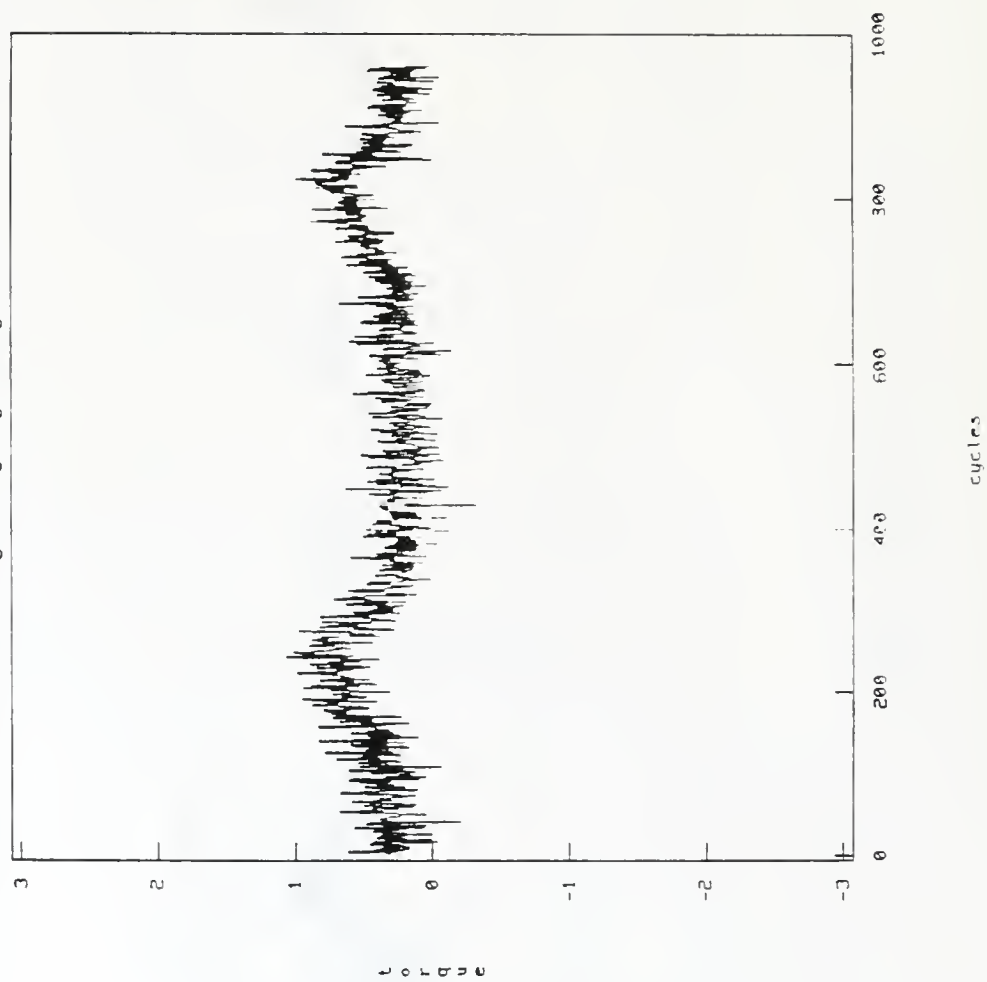


Figure 17: Forces on reference point
(Smaller crank arm length & 50 g wt.)

Figure 17.1: Actual forces

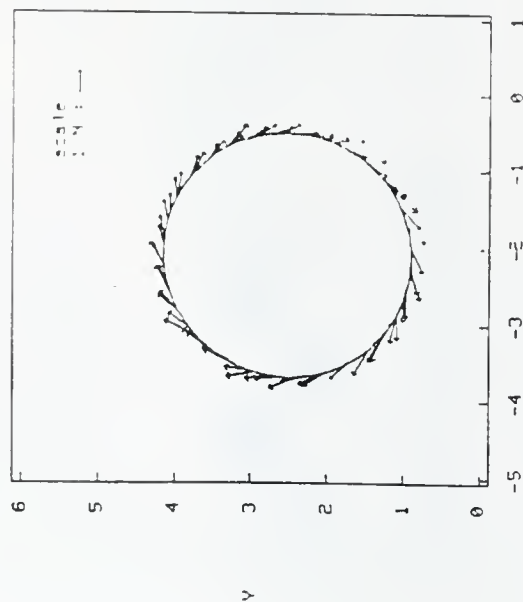


Figure 17.2: Magnitude of forces

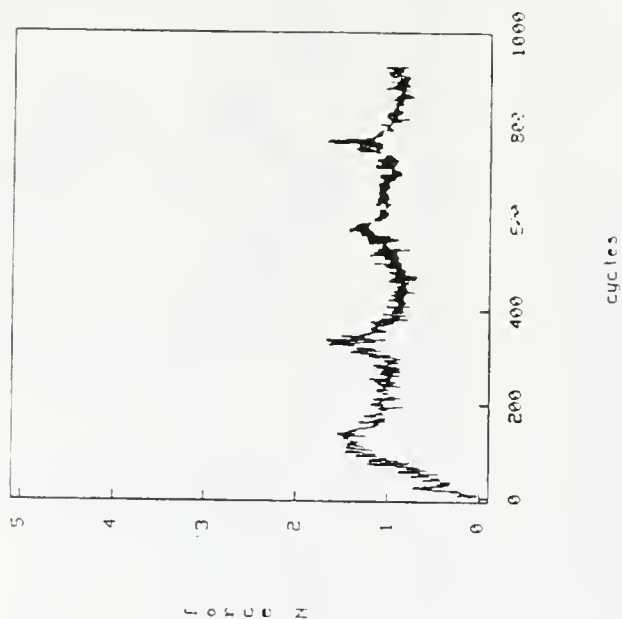
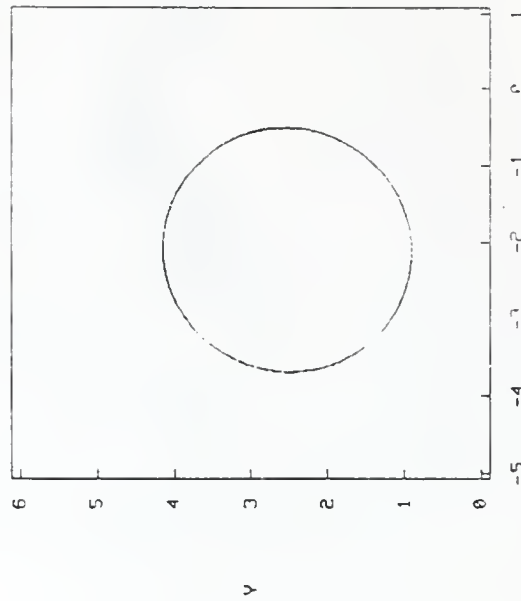


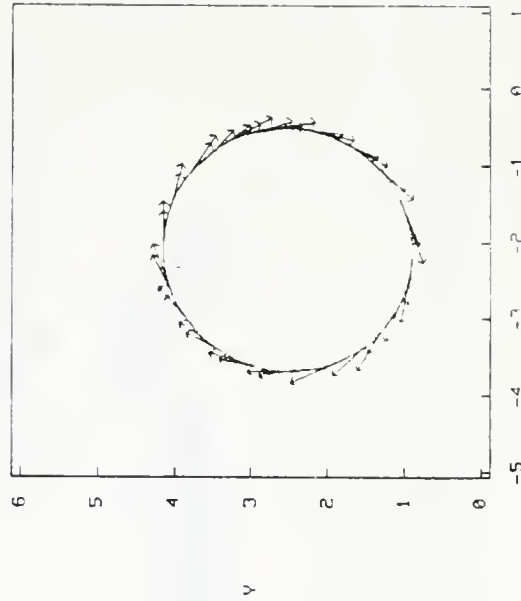
Figure 18: Estimated and Actual paths
(Smaller crank arm length & 50 g wt.)

Figure 18.1: Actual path of ref. point



ref. point location X, (cm)

Figure 18.2: Estimated directions



ref. point location X, (cm)

Figure 19: Forces on each finger
(Smaller crank arm length & 50 g wt.)

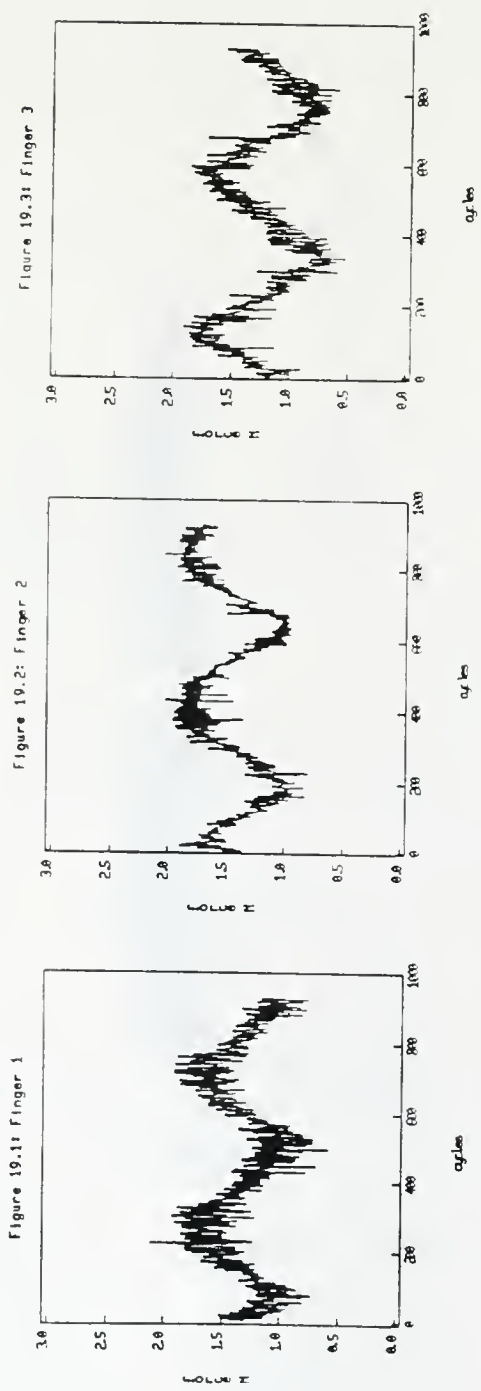


Figure 20: Torque on the reference point
(Smaller crank arm length & 50 g wt.)

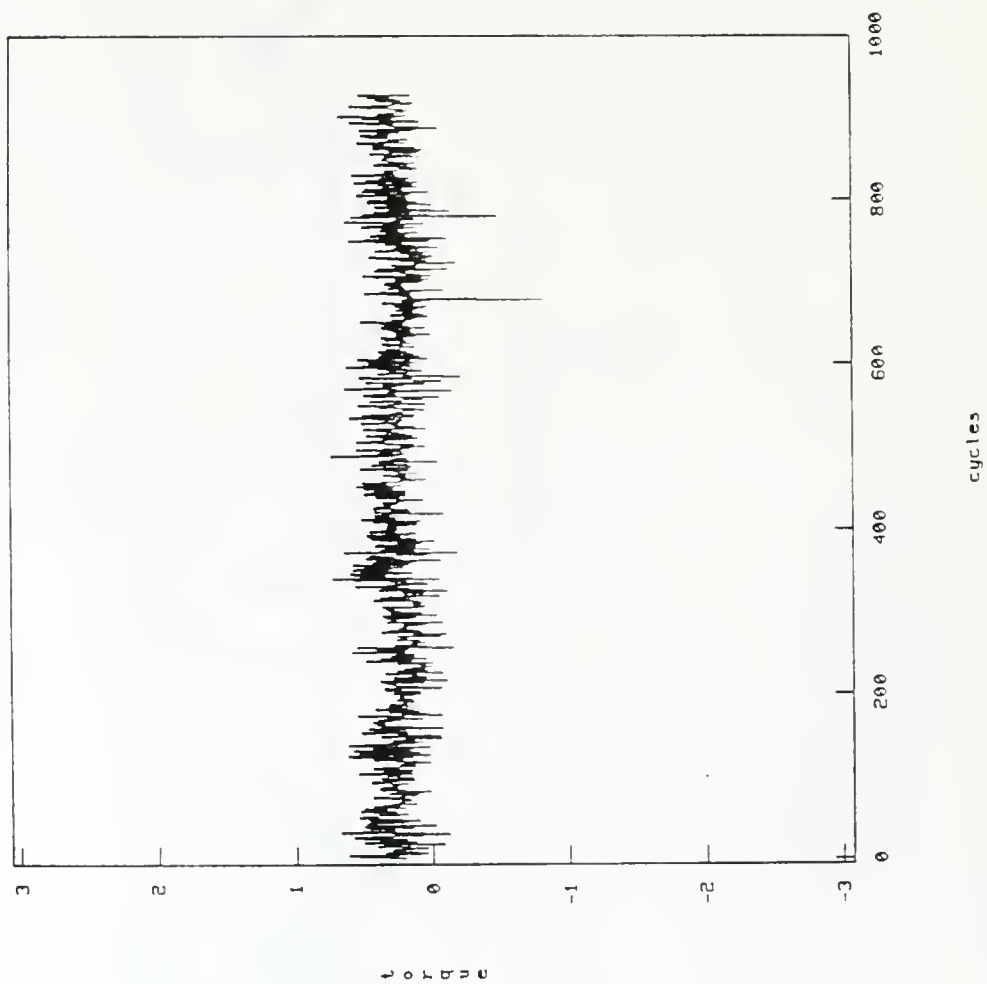
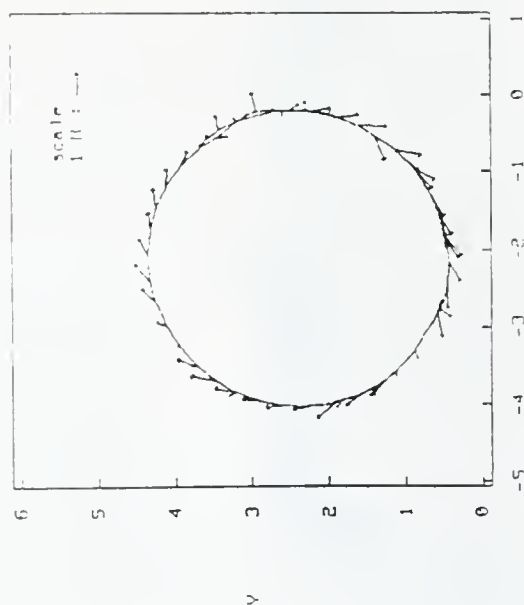


Figure 21: Forces on reference point
(Varying weight upto 50 g.)

Figure 21.1: Actual forces



ref. point location X . (cm)

Figure 21.2: Magnitude of forces

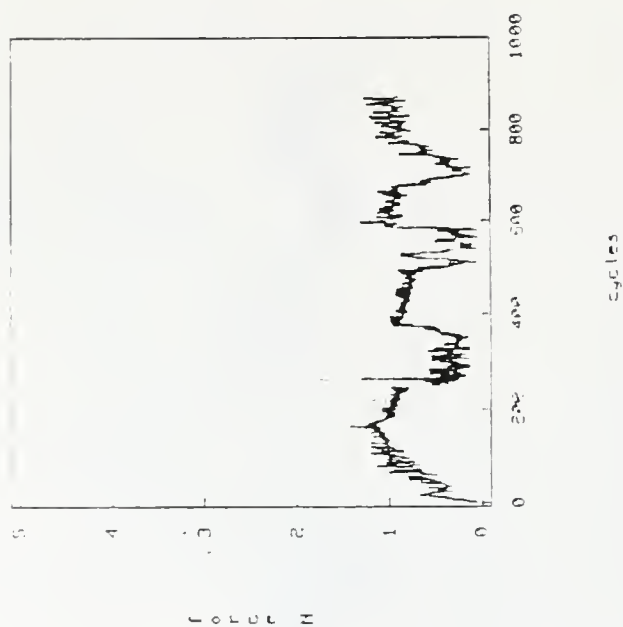


Figure 22: Estimated and Actual paths
(Varying weight upto 50 g.)

Figure 22.1: Actual path of ref. point

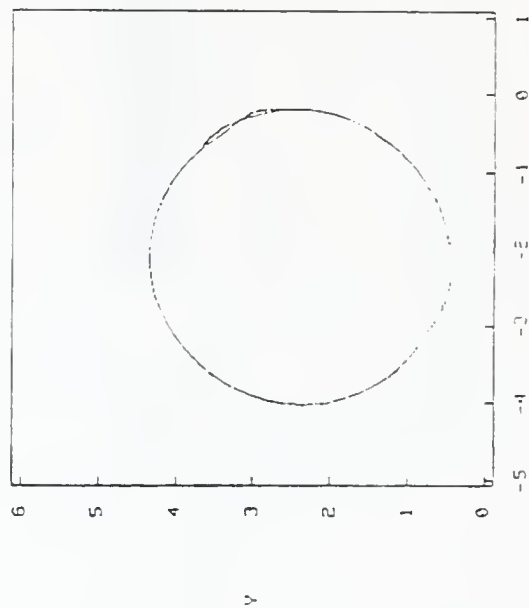


Figure 22.2: Estimated directions

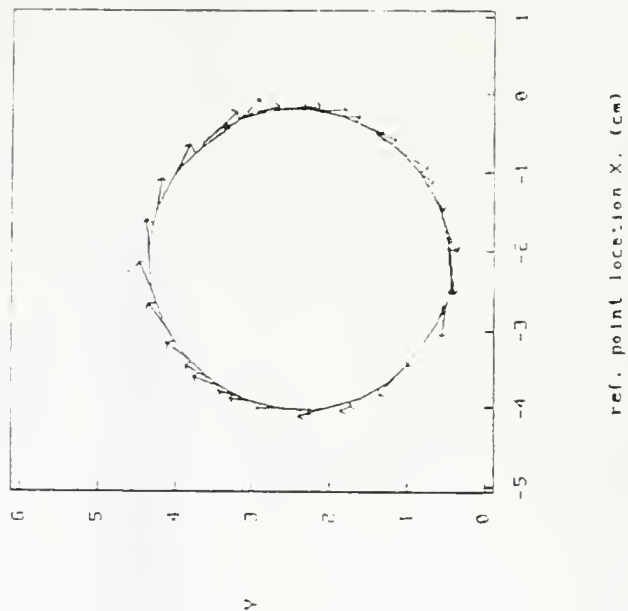


Figure 23: Forces on each finger
 (Varying weight upto 50 g.)

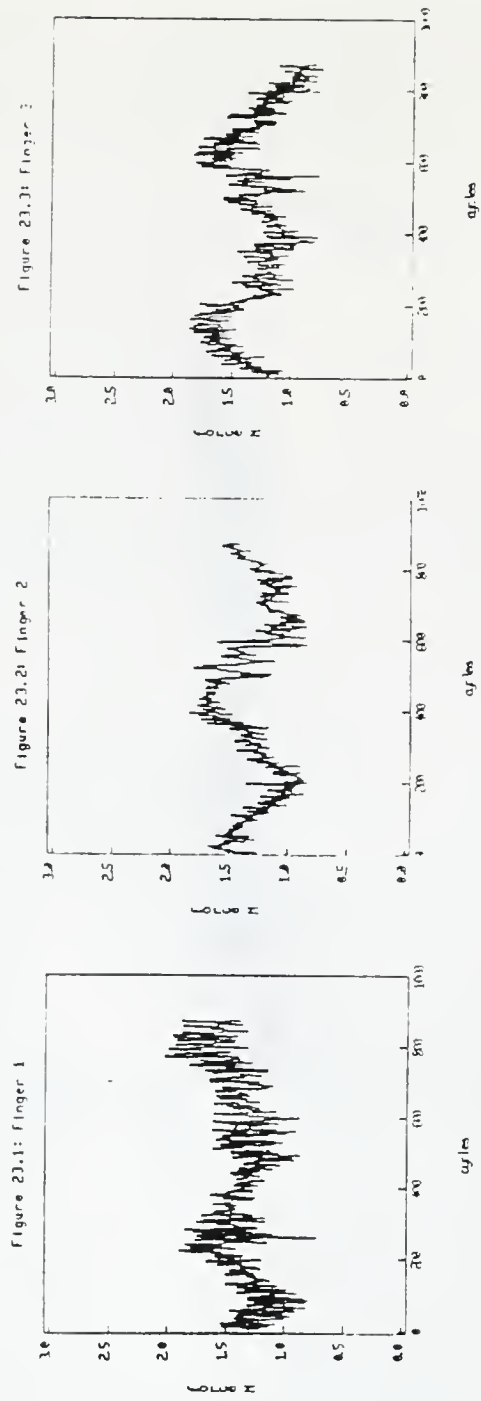
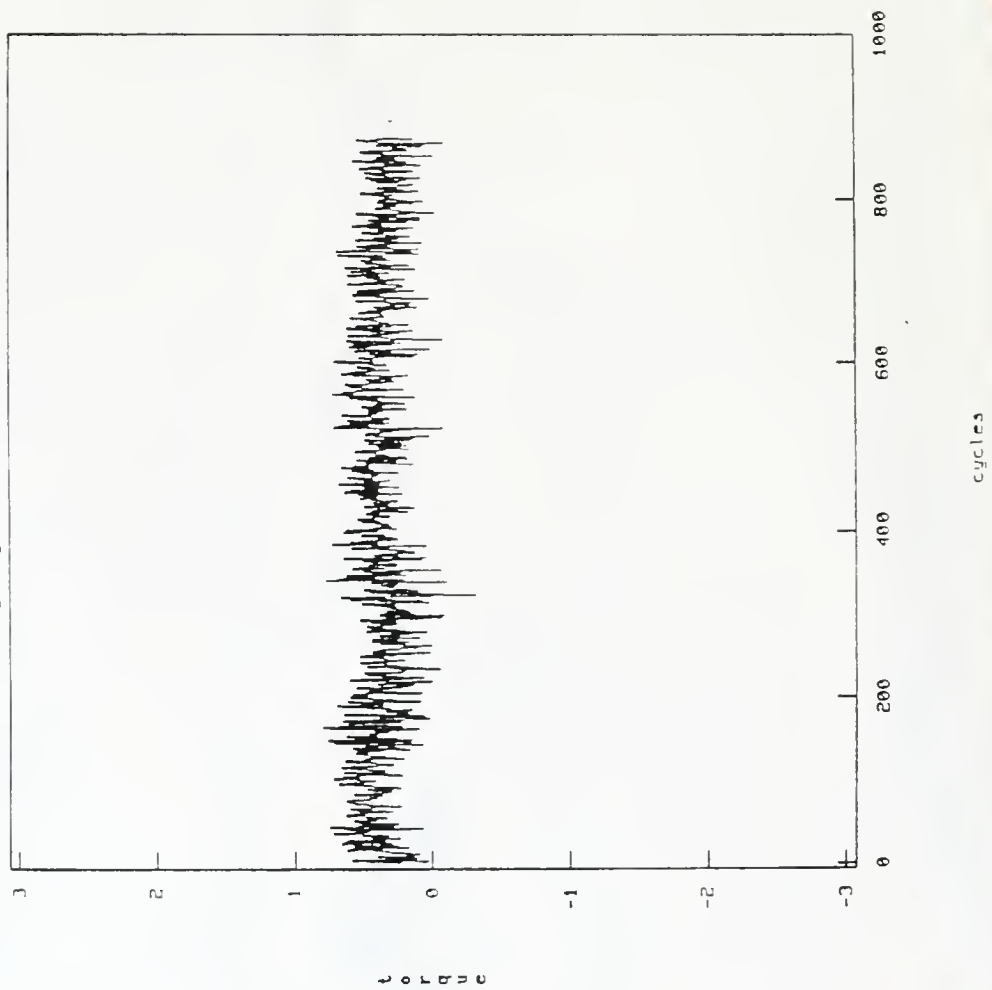


Figure 24: Torque on the reference point
(Varying weight upto 50 g.)



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